Nonlinear Terahertz Gain Estimated from Multiple Photon-Assisted Tunneling in Resonant Tunneling Diode

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We report nonlinear terahertz (THz) gain due to the inter-quantum well subband transitions estimated from current change under THz irradiation in resonant tunneling diodes (RTDs). Due to large THz field induced across RTDs, multiphoton process and reduction of gain with incident power were obtained.

THz emission and amplification utilizing intersubband transitions in quantum well structures are widely studied. In the midinfrared range, quantum-cascade lasers have been realized, and it is hoped that these lasers could be extended into the THz range. In discussing these lasers, the optical gain is one of the most important parameters. We previously reported an estimation of the linear gain under low power irradiation of THz electromagnetic waves[1]. In this paper, we estimated the nonlinear (power-dependent) gain under relatively large irradiation power.

Figure 1 shows schematic illustration of interwell transitions under the THz irradiation in a triple-barrier RTD, where n denotes the n-photon transition (n>0 for absorption, and n<0 for stimulated emission). Many tunneling current passes are made due to the photon-assisted tunneling[2] with multiphoton processes. The device current with these multiphoton processes is approximated as $I = \sum_n C_n I_{dc}(V_{dc} + n\alpha\hbar\omega/e)$, where $I_{dc}(V_{dc})$ is the I-V curve without THz irradiation, C_n is the transition probability resulting in the gain and loss, and α is the ratio of the bias voltage to the voltage between the wells[3,4]. To observe these transitions, GaInAs/InAlAs triple-barrier RTDs integrated with patch antennas[3,4] were prepared. Diameter of the RTD is 1μm and the peak current density is 120A/cm^2. To induce large THz field across the RTDs, the substrate was covered with Au and a large antenna cavity was formed with 3μm-thick benzo-cyclo-butane (BCB) [4].

Figure 2 shows measured I-V characteristics at room temperature for irradiation frequency f=1.4THz. Double peaks were observed under the THz irradiation. The multipeak shape as in [2] was smoothed out in this measurement because the peak width of $I_{dc}(V_{dc})$ is larger than $\alpha\hbar\omega/e$. Instead, the peak shift with increasing THz power was observed, attributed to the increase of n in the multiphoton process. By fitting the above equation to the measured curves, C_n's were determined at each irradiation power. Figure 3 shows the estimated current components of the n-photon processes ($C_n I_{dc}(V_{dc}+n\alpha\hbar\omega/e)$) . The optical gain coefficient for fundamental transition (n=±1) was estimated from the difference between emission and absorption components as in [1], as shown in Fig.4. The peak gain coefficient is ~0.4cm^{-1} in the low incident power region and decreases with THz voltage induced across the RTD.

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[2] H.Drexler, J.S.Scott, S.J.Allen, K.L.Campman and A.C.Gossard, Appl. Phys. Lett. **67** (1995)2816.
[3] Y.Oguma, N.Sashinaka, and M.Asada, Jpn. J. Appl. Phys. **38** (1999) L717.
[4] N.Sashinaka, Y.Oguma, and M.Asada, Jpn. J. Appl. Phys. **39** (2000) 4899.

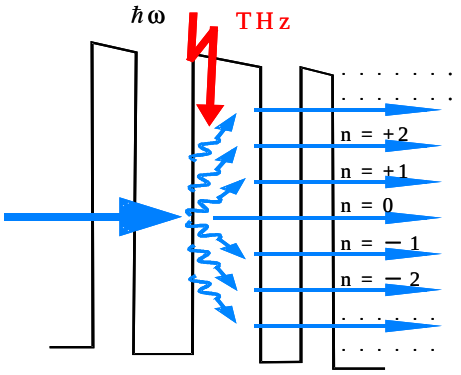

Fig.1 Schematic diagram of photon-assisted tunneling with multiphoton process in a triple-barrier resonant tunneling diode. *n* denotes the *n*-photon process (*n*>0 for absorption and *n*<0 for stimulated emission).

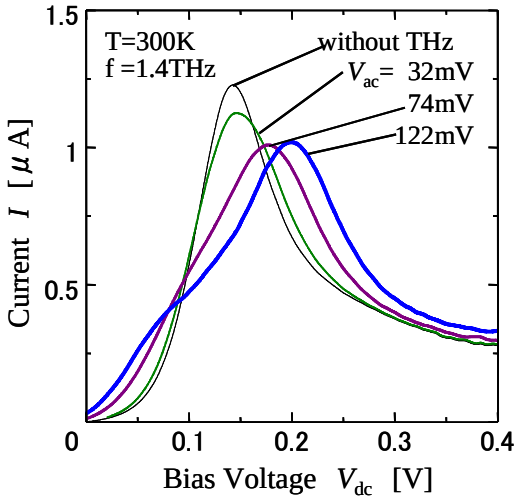

Fig.2 Measured *I-V* curves under THz irradiation of GaInAs/InAlAs triple-barrier resonant tunneling diode. V_{ac} is the THz voltage induced across the diode.

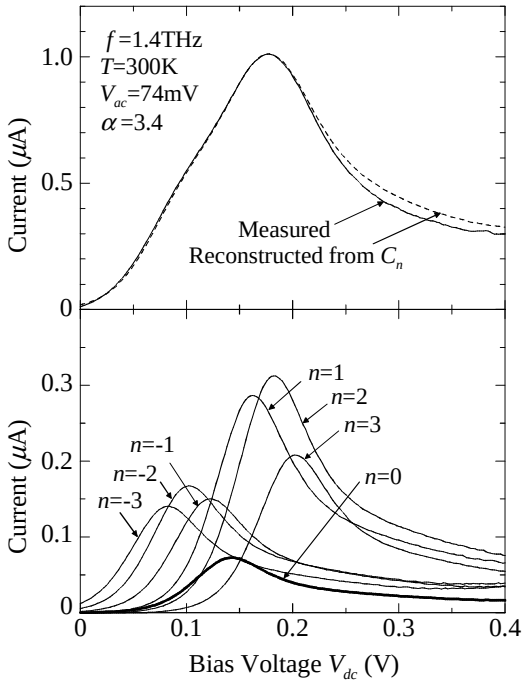

Fig.3 Current components of the *n*-photon process decomposed from the measured *I-V* curve under THz irradiation.

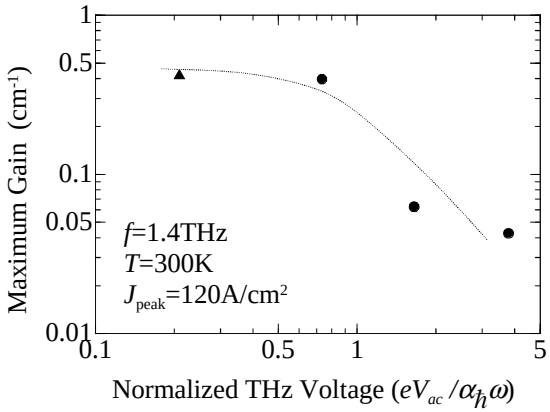

Fig.4 Estimated gain coefficient for fundamental transition (*n*=±1) as a function of THz voltage induced across the diode. Closed triangle is a data from [1] with the change in peak current density taken into account.